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The following document reports the results of the Stanford Workshop on Surgical Simulation. The goal of this workshop was to bring together researchers and developers from around the world who focus on modeling and simulation of deformable materials for applications requiring real-time interaction. We were particularly interested in medical applications including simulation-based training, skills assessment and planning, as well as other non-medical domains where real-time interactivity is needed. Presentations defining the status of the field and helping articulate future directions and possibilities, as well as focusing on the algorithmic, modeling and real-time issues that affect the fidelity and applicability of deformable material simulation to medical and other applications were encouraged. Topics included but were not limited to: Tissue modeling techniques, Simulation methods for deformable objects, Collision detection and handling involving deformable bodies, Topological changes on deformable models (cutting, suturing, cautery tool-use, etc), Bio-fluid modeling, Non-medical deformable material modeling, Immersive visualization methods, Haptic interaction methods.

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Introduction

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Body

In the following a list of participants to the workshop is reported. Following such list the abstracts that have been presented during the workshop are reported. The abstracts are listed alphabetically by author.

S W
S S

List of Participants

List of Participants

(In alphabetical order)

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SWSS

Abstracts & Links

Remis Balaniuk
Research Associate, CATSS Lab, Stanford University

"LEM - An Approach for Real Time Physically Based Soft Tissue Simulation"

This paper presents LEM - Long Elements Method, a new method for physically based simulation of deformable objects, suitable for real time animation and virtual environment interaction. The approach implements a static solution for elastic global deformations of objects filled with fluid based on the Pascal's principle and volume conservation. The volumes are discretized in long elements, defining meshes one order of magnitude smaller than tetrahedral or cubic meshes. The physics of the objects are modeled using bulk variables: pressure, density, volume and stress. No pre-calculations or condensations are needed. The approach is particularly interesting for soft tissue real time simulation and for graphic and haptic rendering.

Cagatay Basdogan
Ph.D., Virtual Environments Laboratory, JPL-California Institute of Technology

"Real-time Dynamics of Deformable Finite Element Models"

We present two efficient methods for simulating real-time dynamics of a deformable 3D object modeled by finite element equations. The first method is based on modal analysis, which utilizes the most significant vibration modes of the object to compute the deformations in real-time for applied forces.
The second method uses the spectral Lanczos decomposition to obtain the explicit solutions of the finite element equations that govern the dynamics of deformations. Both methods rely on modeling approximations, but generate solutions that are computationally faster than the ones obtained through direct numerical integration techniques. In both methods, the errors introduced through approximations were insignificant compare to the computational advantage gained for achieving real-time update rates.

Joel Brown
PhD student, Stanford University

"A Microsurgery Simulation System"

Computer systems for surgical planning and training are poised to greatly impact the traditional versions of these tasks. These systems provide an opportunity to learn surgical techniques with lower costs and lower risks. We have developed a virtual environment for the graphical visualization of complex surgical objects and real-time interaction with these objects using real surgical tools. An application for microsurgical training, in which the user sutures together virtual blood vessels, has been developed. This application demonstrates many facets of our system, including deformable object simulation, tool interactions, collision detection, and suture simulation. Here we present a broad outline of the system, which can be generalized for any anastomosis or other procedures, and a detailed look at the components of the microsurgery simulation.

John Canny and Yan Zhuang
UC Berkeley

"Real-Time Simulation of Global Deformation"

Surgical simulation for haptics is a great challenge. Tissue deformations are large, material properties are time-dependent and non-linear, and tissue geometry changes due to cutting. In this work, we focus on fixed-geometry models. We were able to demonstrate real-time performance with non-linear strain and thousands of elements. We explored two techniques to accelerate mass matrix inversion (the bottleneck): nested dissection and diagonalization. Nested dissection is more expensive but models dynamics exactly. Diagonalization lumps mass to nodes and is similar dynamically to spring-mass models. We used diagonalization in our real-time simulations. We extended the model above in two ways: (i) addition of an impulse response to contacts on the surface of the model. Our impulse response step is constant-time, so simulations run in real time even with many impacts. (ii) use of a "graded mesh" for the model interior. The stress in an elastic material is low-passed filtered by the material itself. It turns out that elements can be graded with size that increases with distance from the boundary, without losing accuracy in the computed strains. Such a graded mesh is one order of magnitude smaller than a dense mesh (O(n^2) vs. O(n^3)). To put it another way, a graded mesh has the same asymptotic number of elements as a surface mesh, and yet accurately models the internal state of the material, even with non-linear strain.

Gregory S. Chirikjian
Professor Mechanical Engineering (secondary appointment in CS)
Johns Hopkins University

"Closed-Form Primitives for Generating Volume Preserving Deformations"

In this talk, methods for generating closed-form expressions for locally volume preserving deformations of general volumes in three dimensional space are introduced. These methods have applications to computer aided geometric design, the mechanics of materials, and realistic real-time simulation and animation of physical processes. In mechanics, volume preserving deformations are intimately related to the conservation of mass. The importance of this fact manifests itself in design, and in the realistic simulation of many physical systems. Whereas volume preservation is generally written as a constraint on equations of motion in continuum mechanics, this talk develops a set of physically meaningful basic deformations which are intrinsically volume preserving. By repeated application of these primitives, an infinite variety of deformations can be written in closed form. As time permits, we will also discuss metrics for rating how different two deformations are from one another.

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1. Chirikjian, G.S. ''Closed-Form Primitives for Generating Volume Preserving Deformations." ASME Journal of Mechanical Design}. 117(Sept. 1995): 347-354.
2. Chirikjian, G.S., Zhou, S., ''Metrics on Motion and Deformation of Solid Models,"
ASME J. Mechanical Design, Vol. 120, No. 2, June, 1998, pp. 252-261.

Francois Conti
Robotics Laboratory, Stanford University

"Tissue modeling via space filling elastic spheres"

Simulating the dynamics of complex deformable solids in real time requires minimizing the computer cycles for processing the physical models. In this project we define a physical model by filling the surface mesh of the object with spheres representing sections of mass of the solid. Spheres are connected together with spring-damper links where the coefficients are defined for each degree of freedom such as extension, torsion and flexion. Finally each vertex of the mesh is connected to the skeleton (spheres and links) to follow the behavior of the physical model. Using the properties of spheres we are also able to compute fast collision detection between multiple solids. Finally we present the connection to a haptic device for real time manipulation.

Stephane Cotin and Paul Neumann
Lead Investigators, CIMIT / MGH

"CAML: A generic framework for medical simulators"

We are currently developing a generic open source software framework for computer-based medical simulators called CAML (Common Anatomy Modeling Language). We believe that CAML will simplify the development time of simulators, and permit components to be shared between different groups. Since this initiative is in its early stages, we want to increase the awareness surrounding this project, get feedback on its current proposal, and encourage others to participate in the project.

Diego d'Aulignac
INRIA Rhone-Alpes - Projet SHARP

"Modeling interaction with deformable objects in real-time"

Most surgical simulations require modeling of deformable objects. Given an appropriate elastic model we may either solve for an static equilibrium or analyze the evolution of the system with respect to time. We present both non-linear static solutions and various time integration methods (notably explicit and implicit) and discuss their relative merits in the context of surgery simulation. Models of the human liver and thigh are used to exemplify the process.

Steve Dawson
MD, Massachusetts General Hospital, CIMIT

"The Missing Links: What the Simulation Industry Needs from Academia"

In its 1999 report, "To Err is Human", the Institute of Medicine explicitly challenged the medical and engineering communities by stating that medical simulation should be developed as a means of reducing medical errors. This moment of opportunity has arrived at a critical juncture for medical simulation. Until recently, simulation development was driven by producers who used the best available technologies to produce technical devices that purported to teach appropriate medical techniques.

Essential elements of realism, authenticity and validation must be present before organized medicine will accept a fundamental change in the methods of medical training which have been in place for 4000 years. However, proof of transferable learning through simulation has been slow to arrive, in large part because elements recognized by physicians as essential to learning have been lacking in available simulators. While skills trainers may teach better hand-eye coordination, judgment and decision making have not been tested, because realistic simulators have not been validated. The challenge facing simulation is how to move from what industry has so far produced to a level of authenticity which will receive the imprimatur of governing authorities, such as medical specialty boards.

The CIMIT simulation program was funded to address key elements of this essential infrastructure science. As the CIMIT program evolves, we will team with other major academic research centers to leverage existing programs into a national collaboration. We must initiate an intelligent national research agenda to address the challenge given to us by the Institute of Medicine.

Einar Haug
Senior Scientist, SimSurgery AS

"Digital Training Simulator for Robotic Assisted Endoscopic CABG"

New robotic assisted procedures require quite different skills than conventional surgical techniques, thus, the need for facilitating the education and training process is very important. Virtual reality surgical training is an educational method ideal with telemanipulating systems. We here report our experiences in developing a simulator for robotic assisted endoscopic CABG procedure by first focusing on the anastomosis part of the operation. We wanted to produce a virtual environment that in addition to instrument coordination also reflects the anatomy and tissue mechanics similar to clinical situations.

METHODS:
In collaboration with the surgical simulator company SimSurgery(tm) (http://www.SimSurgery.no) we explored a new mathematical tissue representation suitable for surgical simulators that exhibit simulated tissue responses similar to the real viscoelastic anatomy. A computer simulated suture model was also developed.

RESULTS:
In our prototype the suture model was integrated with our new platform for modeling three-dimensional (3D) tissue structures comprising a simulated IMA and a simulated LAD, integrated with simulated model of a beating heart. Interaction between the simulated tissue and instruments, like the suture penetrating the vessel walls, appeared realistic, but need further development before essential features as bleeding and tactile responses can be implemented.

CONCLUSIONS:
By computer assisted training the number of animal trails in training with robotic systems can be reduced, and more important, the overall clinical performance can be significantly improved. The technology and experience obtained from simulating robotic procedures render training methods applicable also to conventional techniques.

Wm. LeRoy Heinrichs
MD, PhD, SUMMIT

"Looking Back; Thinking Forward About Surgical Simulation"

The history of Man is characterized by descriptions of people, places, and things! In the context of surgical simulation, the earliest advocate of the training of surgeons more than two millennia ago utilized common objects for "going through the motions", an expression that still describes surgical practice. Some of these objects remain in use currently in "*in vitro*" labs for videoendoscopic surgery. In the 16th Century, paper and wax models became the surrogates for cadavers for students of anatomy, and soon thereafter in the Qing Dynasty, 'Chinese medicine dolls' made of ivory became the vehicles for transferring information between patients and healers. Also in the 16th Century, the articulated metal manikin attributed to Hieronymus Fabricius, was assembled for teaching about fractures and their clinical repair. Another simulation 'machine' used in medical education was the pelvic and fetal models made of wood, leather, and cloth for teaching obstetrical delivery. Hundreds of these were made and used throughout France during the 18th Century by Madam du Coudray, the King's Midwife; one exists today in a French museum. In the 19th Century, moulages (molds) were used to teach restorative surgery of the face. In the late 20th Century, development of computer-based simulators mushroomed to include multiple anatomic regions and surgical procedures. The Visible Human Project of the National Library of Medicine and the Stanford Visible Female (Lucy 2.0), a set of 3D models created of a reproductive age female (pelvis), are being used to support physics-based surgical simulation. Most simulators remain to be formally evaluated and successfully incorporated into clinical education, except by early adopters. An exception may be the ePelvis that is being used on two continents, but even this simulator of the female pelvic exam is mainly used in a research mode. As we enter the 21st Century, medical simulations are being prepared for distance learning via the Next Generation Internet, which will also enable haptic perceptions. The common quest of simulation approaches over the centuries has been the creation of a hands-on experience for learning that substitutes for the 'real thing'. Even now, we continue the quest for ideal simulations to inform classroom learning; only the technology changes! But, current methods that enable both visualization and haptics, providing immediate feedback to learners, and the quantitative assessment of the simulators' efficacy and learners' performance – that's new, and changes how we must think!

http://summit.stanford.edu/Lucy/
http://haiti.stanford.edu/~ngi/final/
leroy.heinrichs@stanford.edu

Thomas M Krummel, MD
Emile Holman Professor and Chair, Department of Surgery
Stanford University

"Surgical Simulation: To Err is human"

In the United States, medical care consumes approximately $1.2 trillion annually (14% of the gross domestic product) and involves 250,000 physicians, almost 1 million nurses, and countless other providers. While the Information Age has changed virtually every other facet of our life, the education of these healthcare professionals, both present and future, is largely mired in the 100-year-old apprenticeship model best exemplified by the phase "see one, do one, teach one." Continuing medical education is even less advanced. While the half-life of medical information is less than 5 years, the average physician practices 30 years and the average nurse 40 years. Moreover, as medical care has become increasingly complex, medical error has become a substantial problem. The current convulsive climate in academic health centers provides an opportunity to rethink the way medical education is delivered across a continuum of professional lifetimes. If this is well executed, it will truly make medical education better, safer, and cheaper, and provide real benefits to patient care, with instantaneous access to learning modules. At the Center for Advanced Technology in Surgery at Stanford we envision this future: within the next 10 years we will select, train, credential, remediate, and recredential physicians and surgeons using simulation, virtual reality, and Web-based electronic learning. Future physicians will be able to rehearse an operation on a projectable palpable hologram derived from patient-specific data, and deliver the data set of that operation with robotic assistance the next day.

J. Harvey Magee(1) and Dr. Gerald Moses (2)
(1) SHERIKON, Inc., an Anteon Company, under contract to the Telemedicine and Advanced Technology Research Center (TATRC), HQ US Army Medical Research and Materiel Command (MRMC), Ft. Detrick, Maryland
(2) Telemedicine and Advanced Technology Research Center (TATRC), HQ US Army Medical Research and Materiel Command (MRMC), Ft. Detrick, Maryland

"Military Medical Modeling and Simulation in the 21st Century"

Military medicine struggles with critical issues. How do we train medical personnel in peace to deliver medical care in war? In 1998, the General Accounting Office reported, "military medical personnel have almost no chance during peacetime to practice battlefield trauma care skills. As a result, physicians both within and outside the Department of Defense (DOD) believe that military medical personnel are not prepared to provide trauma care to the severely injured soldiers in wartime..."
Some of today's training methods are disappearing, the challenges of training are more difficult, and impediments to training, e.g., restricted animal use, costs of live mass casualty exercises, are increasing. To address these challenges, four categories of medical simulation are emerging: PC-based multimedia, digital mannequins, virtual workbenches, Total Immersion Virtual Reality. Success requires a strategic plan, single-agency integration, excellent scientific research in "enabling technologies", sound business practices, and integrated efforts among domain experts in their own fields, e.g., physicians, nurses and "combat medics", working side by side with engineers, computer scientists, designers, experts in education and training, human factors engineers, and managers, to ensure development of effective training devices that will enhance our limited hands-on training opportunities and revolutionize how we train in peace...to deliver medicine in war.

Dinesh Manocha
UNC Chapel Hill
Joint work with Ming C. Lin, Stephen Ehmann, Susan Fisher, Kenny Hoff, Young Kim and Andrew Zaferakis

"Fast Proximity Queries for Simulating Rigid and Deformable Models"

Many applications of computer simulated environments require spatial or proximity relationships between objects. In particular, dynamic simulation, haptic rendering, surgical simulation, robot motion planning, virtual prototyping, and computer games often require many different proximity queries simultaneously at interactive rates. These include collision detection, intersection, minimum separation distance, penetration depth, and contact points and normals. It is a major challenge to perform all these queries at interactive rates on complex and deformable models. In this talk, we give a survey of our recent work on fast proximity queries. It includes:
1. Use of multi-resolution techniques and hierarchical approaches
2. Incremental algorithms for penetration depth estimation between rigid models
3. Generalized proximity queries between rigid and deformable models using graphics hardware
4. Penetration depth estimation between deformable objects using distance fields.

We demonstrate their application on rigid-body dynamics simulation and finite-element simulation, as well as medical applications.

Dwight Meglan
Chief Technology Officer, Mentice Inc.

"Endovascular intervention training simulator"

The endovascular intervention training simulator reproduces the physics and physiology of the human cardiovascular system such that a person can learn to perform various procedures such as cardiac catheterization. The simulator is a generalized solution to endovascular simulation. The initial content scenarios developed for it center on coronary stenting and lead placement for dual chamber pacing. This simulation is combined with a haptic interface to give the user a natural, correct way to interact with the simulation. In addition there is an instructional system coupled to the simulation that provides a framework for learning from the simulation.

While the specific example described here is for coronary artery intervention, the same principles apply for simulating tool interactions with other vascular anatomy. It is largely a matter of creating new data sets to be input to the simulator to simulate another part of the body. In fact, the current system could be applied to non-vascular interventions without much modification and could even be adapted to flexible endoscopy. For a unique tool, some specific simulation code, which would plug into the existing simulator, might need to be developed for simulating its motion behavior and interaction with tissue.

Beyond training, the same simulation core can be adapted in the future to develop mathematical prototypes of tools and procedures as well as used in conjunction with patient data to perform individualized procedure rehearsals. These are all direct descendents of the simulator described here.

Karol Miller
Department of Mechanical and Materials Engineering, The University of Western Australia

"Non-linear Computer Simulation of Brain Deformation In-Vivo"

The presentation describes realistic computer simulation of deformation of the brain subject to *in-vivo* indentation. This work provides a step towards neurosurgical simulation, with applications to non-rigid registration, virtual reality training and operation planning systems and robotic devices to perform minimally invasive brain surgery. An *in-vivo* indentation experiment is described. The force-displacement curve for the loading speed typical for surgical procedures (10 mm/s) is concave upward containing no linear portion, from which a meaningful elastic modulus might be determined. To properly analyze experimental data, a three-dimensional, non-linear mathematical model of the brain was developed. The model included large deformation, non-linear (hyper-viscoelastic) material properties and non-linear (finite sliding) boundary conditions. The model was solved using the finite element method. Magnetic resonance imaging techniques were used to obtain geometric information needed to create the finite element mesh.

The shape of the force-displacement curve obtained using the numerical solution was very similar to the experimental one. The predicted forces were about 31% lower than those recorded during the experiment. Having in mind that the coefficients in the model had been identified based on experimental data obtained *in-vitro*, and large variability of mechanical properties of biological tissues, such agreement can be considered as very good. By appropriately increasing material parameters describing instantaneous stiffness of the tissue one is able, without changing the structure of the model, to reproduce the experimental curve almost perfectly.

Results obtained using the implicit time integration may serve for calibration of simpler, real-time models. The explicit time integration may allow simulating soft organ deformation in real-time. Numerical studies showed also, that the linear, viscoelastic model of brain tissue is not appropriate for the modeling brain tissue deformation even for moderate strains.

More information about soft organ mechanical properties and computer simulation of brain deformation can be found in the following references, available in .pdf format from www.sciencedirect.com :

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Andreas Nürnberger (1) and Arne Radetzky (2)
(1) University of California, Berkeley
(2) IUL Softwarehouse AG, Holzkirchen, Germany

"Surgiality"

During the training of pilots from year to year more expensive and more complex flight simulators are used and while it is already talked about the usage of simulators for the training of driving novices, surgical training is still performed in traditional ways. This also includes the risky training directly on the patient. Nevertheless, surgeons rely to an increasing part on automations especially for surgical planning and navigation. More than ever tools for education and training, for planning and simulation play an important role not only for training but also in real surgery. In this talk we give a brief overview of our work in this area, which we call Surgiality. This combination of "surgical" and "virtuality" means the creation of artificial worlds in the computer for training and planning of surgical interventions by using actual patient's datasets.

For further information see http://www.surgiality.com/.
The slides of the presentation can be downloaded from
http://www.cs.berkeley.edu/~anuernb/slides/SWSS01/surgiality.pdf

Mark Ottensmeyer
Lead Investigator, Simulation Group, CIMIT, MGH

"In vivo linear elastic property measurement of porcine liver"

Surgical simulation, whether for training or for instrument or procedure prototyping, depends in part on knowledge of the material properties of the tissues in question. Generally speaking, tissue force-displacement responses exhibit non-linearity, anisotropy, inhomogeneity and time dependent features, some or all of which may be important to include in a tissue model. Further, tissue properties tend to change after death, so measurements made on living tissues are preferable to those made on excised samples. A number of devices have recently been developed to measure some of these properties for solid organ tissues in vivo, one of which is the TeMPeST 1-D. The Tissue Material Property Sampling Tool 1-D is a minimally invasive surgical instrument which exerts small normal loads on tissues and simultaneously measures displacement and applied load. It is capable of generating vibratory stimuli up to approximately 80Hz, and has a range of motion of +/- 500um. Through careful selection of mean applied load, and frequency and location of stimulation, it can be used to investigate linear stiffness, non-linear effects, damping/viscous characteristics and inhomogeneity over the surface of an organ such as liver or spleen.

In my talk I'll introduce the TeMPesT 1-D system. I will discuss the geometric and other approximations, and modeling necessary for tissue parameter extraction. I'll go into some detail on the instrument hardware and describe experiments designed to verify the performance of the instrument on known elements and materials. The talk will conclude with discussion about in vivo testing on porcine liver and spleen, currently underway. I'll present the results of preliminary analysis of early experiments, and discuss some of the directions towards which our research is headed.

Dinesh K. Pai
Professor, Department of Computer Science, University of British Columbia, Vancouver, Canada

"Tradeoffs in Interactive Deformation Simulation"

Interactive simulation is not just an effort in making traditional engineering simulations run faster. Rather, it requires designing new types of algorithms which respect real-time constraints first, while being as accurate as possible for the task. It requires a critical analysis of the purpose of the simulation, taking into account the needs and knowledge of the human user of the simulation. It requires integrated multimodal simulation with synchronized visual, haptic, and auditory feedback to the user. It may require new types of reality-based models, which rely on measurements more than on idealized physical models. I will discuss these issues and illustrate them with examples from my group's research, including interactive simulation of deformation, sound, and contact texture, and reality-based modeling of deformation.

http://www.cs.ubc.ca/~pai

Carla M. Pugh
MD, PhD., Stanford University

"The Integration of Simulations in the Medical Curriculum: Collection and Analysis of Electronic Performance Data"

Basic science research and the information age have contributed greatly to the exponential growth in new medical knowledge. As a result, the amount of cognitive and technical skills knowledge that has been inadequately taught and assessed during the four years of medical training is on a sharp incline. In a recent series of experiments evaluating the e-pelvis simulator, innovative data characterizing individual skills performance was collected. Data analyses demonstrate that raw, electronic data collected during simulated clinical exams correlate with written assessment measures. These findings scientifically indicate a clear association between cognitive and technical skills performance. In addition, the results demonstrate specific, objective differences in clinical pelvic examination skills when comparing novice medical students and experienced clinicians, establishing construct validity. Simulations, virtual environments and web-based learning hold the promise of a new era for medical education where sound, innovative methods of self-learning and assessment will be the norm pedagogical experience for future students; forever changing the learning environments we know today.

Karl Reining
Post Doctoral Fellow, University of Colorado Health Science Dept

"Preparing Visible Human Type Data for Finite Element Analysis"

Volumetric data sets (such as those created from the Visible Human Project and subsequent efforts) can be used to create realistic texture mapped polygonal models for both haptic and graphic rendering. They can also be used to generate volumetric meshes for Finite Element Analysis (FEA). The first step toward preparing the volume data for the production of 3-D models is to segment the voxels into distinct anatomic structures. This has the natural extension of adding material properties to the voxels. A less-natural extension is the inclusion of structural sharing information: does the surface of one structure attach to or slide against its neighbor? Another area of interest is compact methods of representing anisotropic properties such as muscle fiber direction. This talk discusses embedding information relevant to analysis and display into the volume data, with a particular bent toward surgical simulation.

Diego Ruspini
PhD student, Stanford University

"Simulation with contact for Haptic Interaction"

We present a general framework for the dynamic simulation and haptic exploration of complex virtual environments. This work builds on previous developments in simulation, haptics and operational space control. The relations between the dynamic models used in simulation and the models originally developed for robotic control are also presented. This framework has been used to develop a simulator that can model complex interactions between generalized articulated mechanical systems and permits direct "hands-on" interaction with the virtual environment through a haptic interface.

Luis Serra
Chief Technology Officer Volume Interactions

"Surgery planning in the Dextroscope"

The DextroscopeT technology is a precise and intuitive tool for the manipulation and visualization of volumetric data (in other words, digitized 3D objects). The Dextroscope idea is to make interacting with computer-generated 3D objects precise, intuitive, comfortable and affordable by overcoming the mouse/keyboard/screen barrier, thus providing direct hand access to the hidden inside of any three-dimensional object.
Unlike conventional VR technologies, the Dextroscope user works seated, with both forearms positioned on armrests. Wearing stereoscopic glasses, the user looks into a mirror and perceives the virtual image within comfortable reach of both hands for precise hand-eye coordinated manipulation.
VizDexter 1.0 is the latest software release that runs on the Dextroscope. This provides:

- loading of patient-specific data, either as DICOM 3.0 and image stacks
- volume rendering & polygonal surfaces
- multimodal fusion and registration
- segmentation tools
- voxel editing (drill, suction)
- measurements of volume, surface and length
- collaboration through the Dextrobeam, or remotely through network

The Dextroscope and VizDexter are products of Volume Interactions. For more information please visit:
www.volumeinteractions.com

Shrivastava Alok M.D. (1), Peabody James O. M.D., and Menon Mani M.D.
(1) M.D., M.Ch.(Urology), Laparoscopic and Robotic Urology Fellow, Vattikuti Institute of Urology, Henry Ford Health System,Detroit,MI,USA

"Robot Assisted Laparoscopic Radical Prostatectomy: Special Considerations for Surgical Simulation"

Laparoscopic Radical Prostatectomy(Lap RP) is a recent addition to armamentarium of urologists for surgical cure of Prostate cancer. We have inducted the da Vinci™ Robot into our Lap RP program to perform Robotic Assisted Lap RP.
The prostates' anatomic milieu poses special challenges and makes Lap RP an extremely difficult procedure to learn and teach. It is the same anatomy of a prostate which gives us unique advantages. This along with taking advantage of the 'strengths and weaknesses' of the da Vinci™ System will make our dream of a surgical simulator possible with today's mainstream technology.
We propose a cost effective simulator, based on scene, hyperlink and animated event sequence model.

Stephen Sorkin
Stanford University

"Efficient Collision Detection for Flexible Objects"

This paper presents an efficient algorithm for determining whether two deformable, non-convex objects are in collision. The algorithm is based on sphere-tree hierarchies and provides a method to quickly adjust the hierarchies when the objects deform. Although the algorithm allows for arbitrary deformations of the objects, the actual collision query remains most efficient when the deformation from the original object remains bounded. Like Quinlan's algorithm on which this work is based, we allow for query-time settable error rates to provide a continuum of information between collision detection and exact distance computation. Empirical evidence demonstrates that the algorithm provides real-time performance on useful-sized models.

Dr. Mandayam A. Srinivasan
MIT Touch Lab

"Multimodal Simulation of Tool - Tissue Interactions: Physics or Phiction?"

Given the complexity of tissue behavior and tool-tissue interactions, it is hard to imagine we will ever be able to have perfect simulations of medical procedures in virtual reality based systems for medical training. However, since human trainees have sensorimotor and cognitive limitations, perfect simulations are not necessary. What level of approximation results in optimal training transfer depends on the goals of training and complexity of the medical procedure. In this talk I will describe a taxonomy of approximations and illustrate it with examples from our work on real-time haptic and graphical simulation of tool-tissue interactions.

Bharti Temkin
Ph.D., Dept. of Computer Science, Texas Tech University

"Haptic Texture Generation – A Heuristic Method For Virtual Body Structures"

We address the question developing a library of three-dimensional Haptic Anatomical Structures (3D-HAS) by integration of haptics with Virtual Body Structures (VBS). Such a library would provide a stepping-stone to integrate haptics for future surgical training simulations. A number of difficulties must be overcome in order to create a realistic sense of touch. One of the problems is that the data of in-vivo tissue compliance properties needed to generate credible output forces does not exist. Once consistent understandable data exists, we will still be faced with the issue of developing force feedback models that can be applied in surgical simulations. Without this "haptic texture", the sense of touch component will remains relatively primitive and unrealistic. In this presentation, we describe a system that generates Virtual Body Structures using Visible Human segmented data and adds haptic texture, thus creating 3D-Haptic Anatomical Structures. The system integrates an algorithm for the generation of VBS with a Graphics-to-Haptic (G_2H) tool that makes arbitrary 3D objects haptic without any additional programming. A method of creating, modifying, and applying heuristic texture data will also be described. The system makes it possible, for an expert in the field of anatomy or surgery, to generate a haptic texture appropriate to a given anatomical structure. Once generated, the haptic texture can be saved as a part of a heuristic database of tissue properties. The goal of this work is to create a library of 3D structures with haptic textures that can be used as canonical models for the development of surgical simulations.

Frank Tendick, Xunlei Wu, Michael Downes, Tolga Goktekin, M. Cenk Cavusgolu, David Feygin, and Gunnar Proppe
University of California, San Francisco and
University of California, Berkeley

"Adaptive Nonlinear Finite Elements for Deformable Body Simulation Using Dynamic Progressive Meshes"

The VESTA (Virtual Environments for Surgical Training and Augmentation) project at U.C. San Francisco, U.C. Berkeley, and U.C. Santa Barbara includes engineers, computer scientists, physicians, and psychologists developing and evaluating simulation systems for surgical training. Our goals are to develop technologies and algorithms for simulation, improve methods of surgical training and education, and to elucidate the cognitive basis of surgical skill.

This presentation will focus on our work in accurate real-time deformable tissue modeling. Past techniques of deformable modeling for real time simulation have either used approximate methods that are not physically accurate or linear methods that do not produce reasonable global behavior. Nonlinear finite element methods (FEM) are globally accurate, but conventional FEM is not real time. We apply nonlinear FEM using mass lumping to produce a diagonal mass matrix, and explicit integration, allowing real time computation scaling as O(n). A major challenge in nonlinear FEM is to maximize offline computation to reduce the computational demand while the simulation is running. In addition, accuracy should be maximized in areas where there is fine detail, and computation minimized elsewhere. The approach we have developed to address these issues is called Dynamic Progressive Meshes (DPM). This is an extension of the progressive mesh method in the computer graphics literature, and works for either triangular or tetrahedral meshes. Parameters for the finite element model are pre-computed at a range of mesh resolutions from coarse to fine in a hierarchy. When the simulation is running, the mesh is refined locally where necessary, such as where instruments are in contact with the tissue. Mechanical properties have been obtained from a variety of abdominal tissues in the pig using in vivo measurement instrumentation we have developed. We are developing key extensions to the DPM method, including fast stress propagation with explicit integration using multi-grid techniques; collision detection and response optimized for DPM; parallelization methods; and modeling fracture (cutting and crack propagation in tissue). Because the DPM model is hierarchical, cutting can occur with minimal re-computation.
In addition, we have developed methods for haptic interaction with simulation, including a multirate scheme for stable haptic interaction at fast update rates using a local linear approximation. We are also exploring the role of kinesthetic feedback and haptic guidance in training complex perceptual-motor skills.

Some information on the project and relevant papers may be found at http://robotics.eecs.berkeley.edu/~tendick/vesta.html.

Matthias Teschner
Ph.D., National Biocomputation Center, Stanford University

"Direct Computation of Nonlinear Soft-Tissue Deformation in Craniofacial Surgery Simulation"

An optimization approach for computing nonlinear soft-tissue deformation due to external forces is introduced. Deformation techniques based on mass-spring models commonly simulate the dynamic behavior of the system due to external forces. In contrast to these methods the introduced static approach directly estimates the resulting stable equilibrium employing an optimization method. The optimization approach is robust and very efficient with regard to computational costs.
Software Demonstration:
The approach to soft-tissue deformation is part of an integrated system for craniofacial surgery simulation. The system is based on a patient's bone model and a photo realistic surface scan of a patient's face. The system can be used to simulate bone cutting and bone realigning with interactive collision detection. It predicts the resulting soft-tissue changes.

Dave Tonnesen
Research Scientist, Starlab and FoAM, Brussels, Belgium

"Sketching of 3D Shapes"

We show that it is currently possible to interactively model complex 3D geometric shapes in a virtual environment in real time. Our implementation uses virtual shaping tools that follow 3D position and orientation of the artist's hand using a six degree of freedom stylus. The tools mimic real world objects by directly deforming the geometric model based on collisions between the tool and model, such that the model locally deforms to the shape of the tool. This talk will also discuss the physically inspired models of deformation using dynamically coupled particle systems.

Payan Yohan
Assistant Professor, TIMC Laboratory

"3D Finite Element Model of the face to predict aesthetic and functional consequences of Plastic and Maxillofacial surgery"

A surgical simulator for plastic and maxillofacial surgery, that gathers the dental analysis (orthodontia) and the craniofacial analysis (cephalometry) into a single computer assisted procedure, has been recently presented and evaluated [1]. This simulator set up a semi-automatic diagnosis for facial bone structure repositioning.

This talk addresses the next step of this work namely predicting the consequences of the simulated bone structures displacements on the patient face appearance. In that purpose, a generic 3D biomechanical model of the human face was developed [2]. This model is based on a multi-layers volumetric mesh, used to discretize the linear elasticity equations in the framework of the Finite Element Method. Biomechanical properties are chosen to replicate observations made on human skin. Face muscles are defined in the mesh as separate structures, with different properties (transverse isotropy, stiffness depending on muscle contraction). Simulations of face deformations under muscles actions can thus be performed.

To couple the face model with the simulations of bone-repositioning, the generic soft-tissues mesh is fitted to patient data by elastic registration, using skull and skin surfaces segmented from a CT exam. This matching process generates a new model, adapted to the patient face morphology. Therefore, after correcting the finite elements that could have been distorted during the registration, the predictions (from an aesthetic and functional point of view) of the deformations of the patient face after surgery can be simulated.

1. Bettega, G., Payan, Y., Mollard, B., Boyer, A., Raphaël, B. & Lavallée, S. (2000). A Simulator for Maxillofacial Surgery Integrating 3D Cephalometry and Orthodontia. Journal of Computer Aided Surgery, vol. 5(3), pp. 156-165.
2. Chabanas M. & Payan Y. (2000). A 3D Finite Element model of the face for simulation in plastic and maxillo-facial surgery. Proceedings of the Third International Conference on Medical Image Computing and Computer-Assisted Interventions - MICCAI'2000, pp. 1068-1075, October 2000, Pittsburgh, USA

Xin Wei, Sha
Assistant Professor School of Literature, Communication and Culture (LCC)Georgia Institute of Technology

It may be helpful to compare experiences with parallel experiences in the community of geometers who have used computer tools for visualization, computation and simulation, and with electronic music performers who have used gesture-based realtime controllers for performance.
In geometry and topology, pepople have built and used detailed representations of topological and geomettrical structure, structural operators, and numerical methods (for evolution and simualtion problems). There are interestimg parallels in needs and debates.

Here are some long-standing experts in differential geometry and computer tools for "visualzation" and "simulation":

- *Ulrich Pinkall, Technische Universität Berlin, Fachbereich Mathematik MA 8-3 Sgb 288 , differential geometry, pinkall@math.tu-berlin.de, www-sfb288.math.tu-berlin.de/*
- *William Thurston, hyperbolic manifolds (Fields medal, Geometry Center, MSRI, etc.), UC Davis*
- *Paul Burchard (Geometry Center), Princeton CS http://www.cs.princeton.edu/~burchard/*
- *Charlie Gunn, (Geometry Center), Oorange ...*

On capillary Surfaces (perhaps useful for contact phenomena like wet threads, films):

- *John McCuan, Georgia Tech Mathematics, mccuan@math.gatech.edu*
- *Robert Finn, Stanford Mathematics, finn@math.stanford.edu*

On soap films, minimal surfaces:

- *John Sullivan, University of Illinois at Urbana-Champaign, Mathematics http://www.math.uiuc.edu/~jms/*
- *At GaTech, John McCuan is interested in investigating physical phenomena related to minimal surfaces and capillary surfaces, and has a long experience with lab-driven physical problems.*

Groups:

- *Geometry Center (defunct NSF center) http://www.geom.umn.edu/*
- *GANG | Geometry Analysis Numerics Graphics http://www.gang.umass.edu/*
- *Mathematical Sciences Reseach Institute http://www.msri.org/ eg. David Hoffman, Scientific Graphics Project*

KEY RESEARCH ACCOMPLISHMENTS:

This meeting brought together together leading researchers in the field of surgical simulation and focused on clarifying the state-of-the-art, identifying emerging capabilities and to articulate research needs. It also help attendees form closer connections to individuals and organizations with complimentary skills and resources.

REPORTABLE OUTCOMES:

- this manuscript containing abstracts relative to the presentations that have taken place during the workshop
- a web page relative to the workshop that can be found at www.robotics.stanford.edu/~swss

CONCLUSIONS: This workshop was one of four meetings supported by seed funding graciously provided by TATRC, covering related topics in telemedicine: Surgical Simulation, Haptics, Digital Human, and Standard/Outcomes. The meeting provided a significant milestone for this growing community and is likely to be the first of an ongoing series of semi-annual meeting. The format and venue were considered ideal by participants. The organizers recommend that future meetings retain the Abstract submission format with perhaps the addition of asking each participant to contribute a one page powerpoint/web page summarizing their work or presentation. It was also suggested that the presentations and discussions be captured by audio recording and transcribed into a textual proceedings.